Design, Manufacturing, and Testing of a Miniature Compression Split Hopkinson Bar

Undergraduate Thesis

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Abstract

A Split Hopkinson Bar is an apparatus that is used to test materials at high strain rates. The typical Split Hopkinson Bar has a length of 6 meters and runs tests at a strain rate between 500 s^{-1} and 5,000 s^{-1}. The limitation of testing at a maximum strain rate of 5000 s^{-1} is becoming more of a problem as technology develops in fields such as space travel or weapon defense. In fields such as these, knowing exactly how a material will react in application is crucial to success. For example, a bullet striking a bullet proof vest creates a strain rate in the range of 10^4 s^{-1}[6]. With current material testing technologies, engineers are unable to know exactly how the material will react in this situation. In order to fix this issue, an apparatus needs to be created which can test materials at strain rates greater than 5000 s^{-1}.

This report focuses upon the design, manufacture, and testing of a Miniature Split Hopkinson Bar. This device alleviates the aforementioned strain rate restraint for certain materials. The Miniature Split Hopkinson Bar is designed to a size of four feet in length and has the ability to test materials at a strain rate of 10^4 s^{-1}.

Acknowledgements

First and foremost, I would like to thank Dr. Amos Gilat for his help with the design and troubleshooting throughout the expanse of this project.

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Chapter 1: Introduction

1A. Background

In the world of material testing there are hundreds of tests that can be done in order to discover a material's properties. Materials can be tested at different loads, orientations, temperatures, etc. In all of these tests, different properties can be found, such as young's modulus, yield strength, or ultimate strength. However, when the environment in which a material is tested changes, the material properties will typically change as well. This change also occurs when testing materials at different rates of strain.

Strain is defined as the change of length divided by the total length of the specimen, given in $\frac{mm}{mm}$. Strain rate is therefore the rate at which a material is strained, given in units of s^{-1}. When materials are strained at different rates, some of the material's properties change.

Figure 1 shows the results of a test completed by Jeremiah Hammer [1]. In this test, he used the same set-up and the same material, but he changed the rate at which he strained the material. As can be seen in Figure 1, two different stress strain curves were produced.

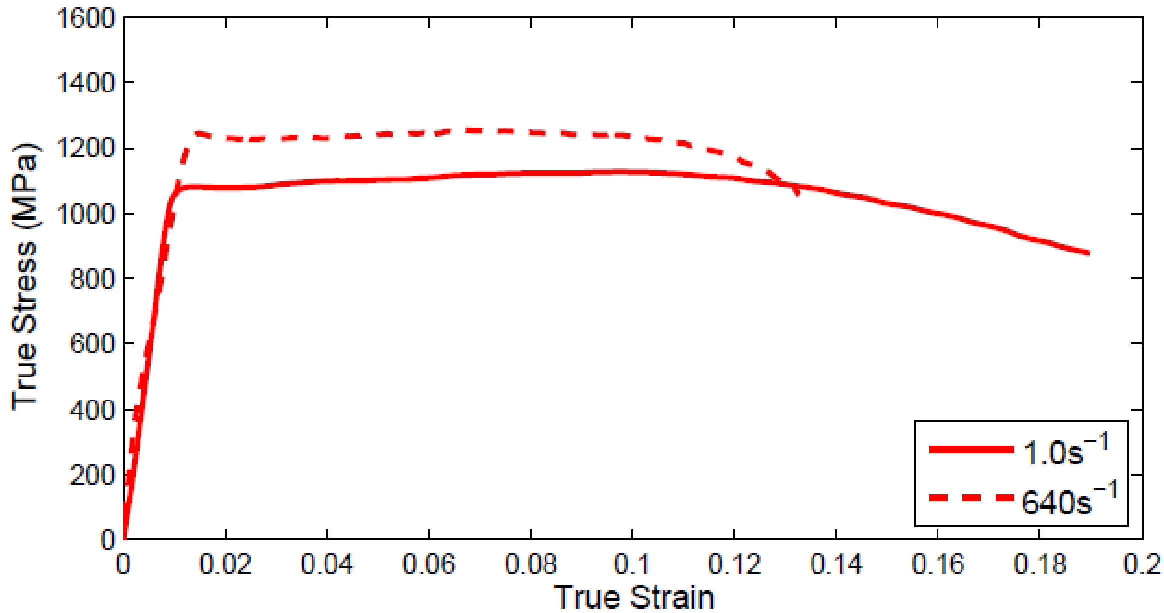

Figure 1: Differing Strain Rates [1]

In order to find material properties at different strain rates through the production of graphs such as the one in Figure 1, an apparatus known as a Split Hopkinson Bar (SHB) or Kolsky Bar is used. This test apparatus is used to discover a material's properties at different strain rates. The typical SHB can test material between strain rates of 200 s^{-1} to 5000 s^{-1}, depending on the test. A SHB can test materials under three different types of loads: compression, tension, and torsion. The basic idea behind all three tests are very similar, but the major difference is how the load is applied. This paper is going to focus on the compression test.

Figure 2 shows the set-up of a Compressive SHB. As can be seen in Figure 2, the SHB consists of three bars, two strain gages, and a system in which a load is applied to the striker bar. In this diagram, that load is depicted as a gas gun.

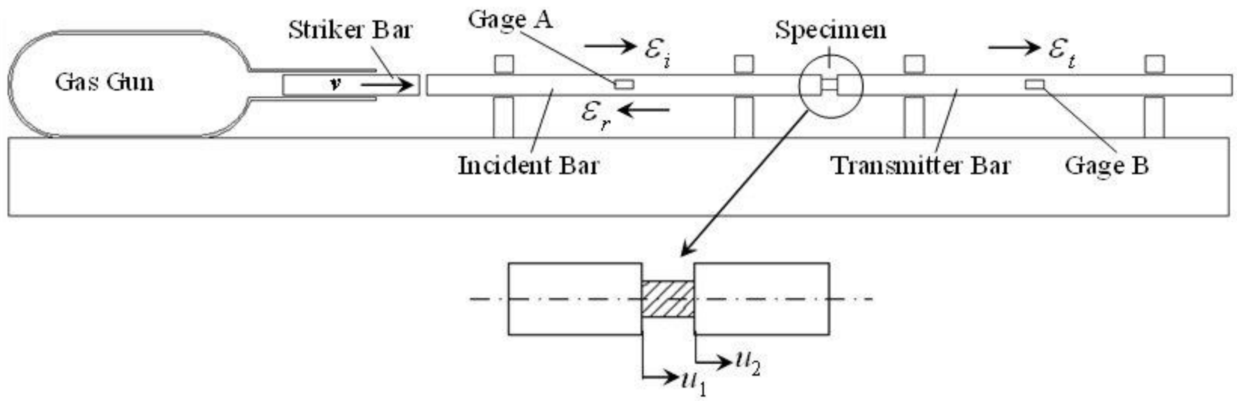

Figure 2: Split Hopkinson Pressure Bar [2]

During the SHB test, a load is applied to the striker bar in order to shoot the striker bar at a desired velocity. This velocity is directly proportional to the strain rate in which the specimen is being tested. Once the striker bar is released, it collides with the incident bar which then applies the load to the specimen. Throughout this test, the strain gauges are picking up three different readings. The first is the incident strain [$\in_i$]. This is the strain caused by the initial impact of the striker bar on the incident bar. The second is the transmitted strain [$\in_t$], or the strain that is transmitted through the specimen and into the transmitter bar. The third is the reflected strain [$\in_r$], or the strain which is reflected back through the incident bar from the specimen. These three strains are then used to create a stress strain curve, such as the one in Figure 1. This stress vs strain curve represents the material's properties at the tested strain rate.

A typical SHB is around 6 meters in length and uses striker, incident, and transmitter bars roughly 25 mm in diameter. The SHB compression test can test materials at a strain rate between 500 and 5000 s^{-1}. This creates a problem when designing a product that incorporates material that will be put through a higher strain rate than 5000 s^{-1}.

To put strain rate into perspective, figure 3 shows a rough diagram of activities that create a strain rate in different materials.

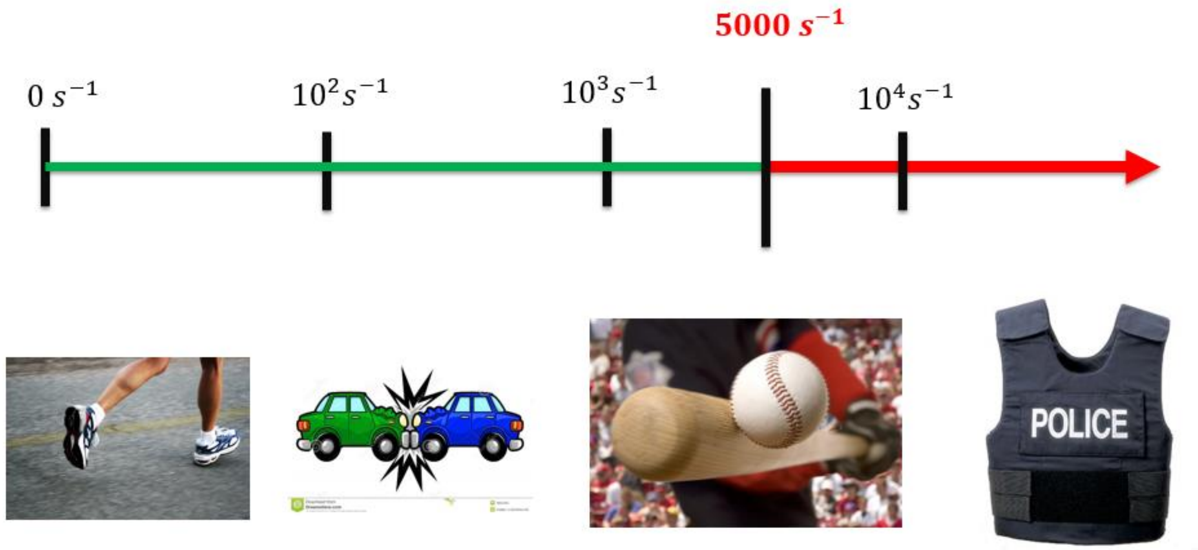

Figure 3: Strain Rates

When running, the human body creates strain on muscles, bones and ligaments. However, the strain rate that is created during this activity is relatively low, typically under 1 s^{-1}[3]. In a car collision there are many different strain rates that occur depending on which parts of the car are being investigated, how quickly the car was moving, and how quickly the car was stopped. However, most of the strain rates that occur in a car accident are in the high hundreds or low thousands of s^{-1}[4]. Similar to car accidents, the strain rate which occurs when striking a baseball is dependent on many factors, such as the speed of the pitch or how solidly the ball is struck. Keeping this in mind, hitting a baseball creates a strain rate in the range of the mid thousands of s^{-1}[5]. Lastly, a bullet striking a bullet proof vest creates an extremely high strain rate because of the large velocity and the large magnitude of deceleration. These strain rates can reach the $10^4 s^{-1}$ or even larger amounts [6].

In figure three, the line graph turns red at 5000 s^{-1} because this is the point where it is no longer possible to test material properties with the current SHB apparatus. This creates an issue in the design process because only estimations can be made about the exact properties of a material with large strain rates. In order to solve this issue, a device needs to be created in order to test materials at high strain rates.

The following chapters explain the design of a miniature Split Hopkinson Bar (MSHB). The design criteria of this research project is to create a Split Hopkinson Bar that is tabletop sized and can reach a compressive strain rate of $10^4 s^{-1}$.

1B. Literature Review

Previous research has been completed in the development of a miniature split Hopkinson Bar. Jamie Kimberly and Justin Paul developed a “Miniature Kolsky Bar” for thin film testing which was tested with an aluminum specimen under tension at a strain rate approaching 10^4 s^{-1}. [7]

The Air Force Research Laboratory has developed a Miniature split Hopkinson bar that can test materials under a compressive strain rate. This MSHB has been used to test copper and polytetrafluoroethylene up to 3.6 x 10^4 s^{-1}. [8]

Chapter 2: Design Criteria

2A. Defined Parameters

Before beginning the design process, certain parameters need to be set. As an initial design parameter, this Split Hopkinson Bar needs to be able to test material at a compressive strain rate approaching$10^4 s^{-1}$, a strain greater than 0.5 mm/mm, and a stress level of 600 MPa. The 600 MPA stress in the specimen was set based on the desire to test stronger materials at these high strain rates.

In order to reach a high strain rate, the SHB will be shrunken down to under 1.2 meters. This Split Hopkinson Bar will be referred to as a Miniature Split Hopkinson Bar (MSHB) for the remainder of this paper.

2B. Bar Lengths

The lengths of the three bars (Striker, incident, and transmitter bars), are dependent upon the material from which the bar is made, the desired strain, and the desired strain rate. The first step is calculating the length of the striker bar.

2B1. Striker Bar Length

In order to find the length of the striker bar, the wave speed through the bar is found. The wave speed is going to be equivalent through all three bars since all three will be made from the same material. The titanium alloy, Ti-6Al-4V, was chosen for the material in the three bars because of its strength and durability, giving the testing apparatus the ability to test a wide range of materials. The titanium alloy's Density (ρ)and young's Modulus (E) are used in calculating the wave speed through the bars. Equation 1 shows the wave speed (C_b) calculation. [9]

$$C_b = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{113.8*10^9}{4430}} = 5.07\frac{mm}{\mu s} \qquad [1]$$

The total time of one test (t_{total}) is found based on the desired strain rate ($\dot{\in}$) and strain ($\in$). This value is then used to find the total time it takes for the wave to travel through the striker bar one time (t_{bar}). These calculations can be found in Equation 2 and Equation 3. [9]

$$t_{total} = \frac{\in}{\dot{\in}} = \frac{0.5}{10^4} = 50\mu s \qquad [2]$$

$$t_{bar} = \frac{t_{total}}{2} = 25\mu s \qquad [3]$$

Once the time it takes for the wave to travel through the striker bar once is found, it is an easy calculation with the wave speed to find the length of the striker bar. This calculation can be found in Equation 4. [9]

$$L_{striker} = C_b * t_{bar} = 126.7mm \qquad [4]$$

2B2. Incident and Transmitter Bar Lengths

Now that the Striker Bar length is known, the lengths of the Incident and transmitter bar can be found. These bar lengths are found based on the strain gage positioning. The positioning of the strain gages need to be in the center of the Incident and transmitter bars in order to read the appropriate wave at the appropriate time. Since that position is set, the lengths of the Incident and Striker bars need to be determined so that the strain gage readings are true to the test. Figure 4 depicts a Time-vs-Position graph which is used to find the incident and Striker Bar lengths

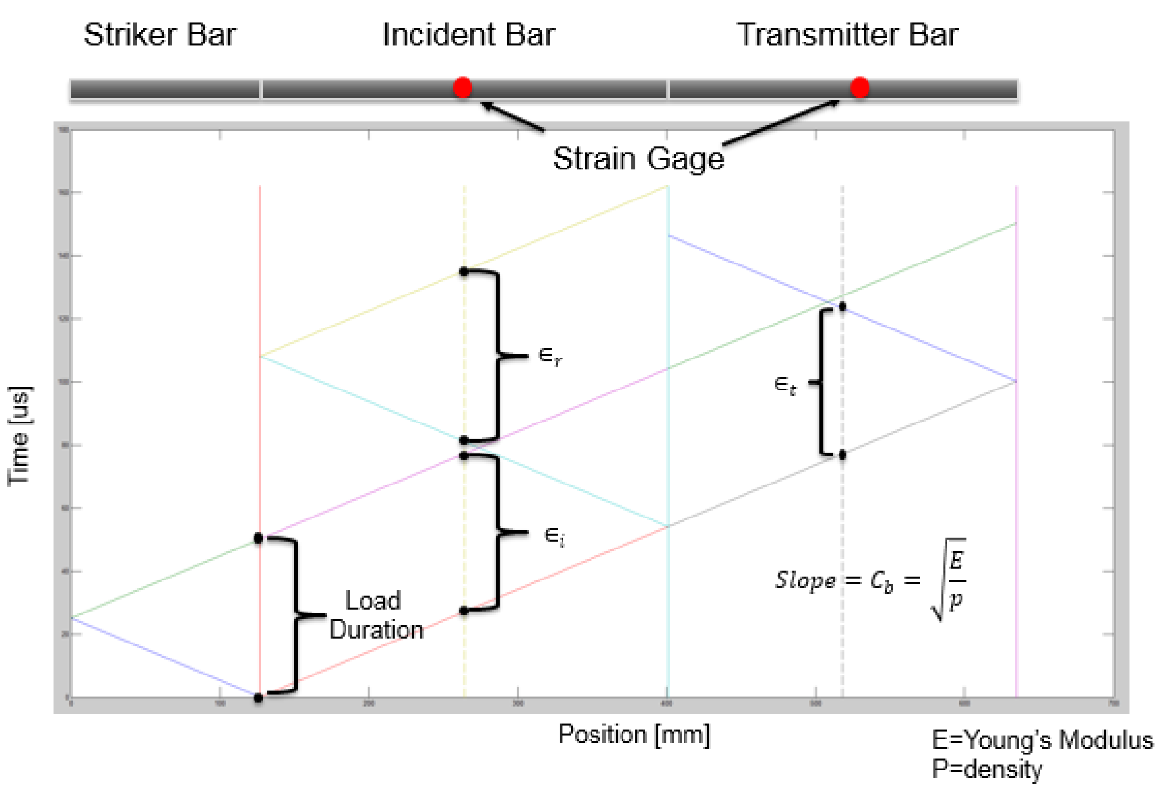

Figure 4: Time-vs-Position graph

The three bars can be seen at the top of figure 4. The red, blue, and purple lines denote the point where the bars would collide if a wave was traveling through them. The dotted yellow and dotted blue lines depict the strain gauges which are located directly in the middle of the two bars. The slanted lines represent the wave propagation through the bars. The slope of this wave propagation is the wave velocity which was found in Equation 1 and is shown in the bottom right hand corner of the plot. The wave propagation begins when the striker bar collides with the Incident bar. This sends out a wave through both bars which can be seen in the bottom left hand corner of the graph. A new wave is then created whenever one of the waves reaches another bar.

These waves that are traveling through the three bars are then picked up by the two strain gages in order to find the incident strain ($\in_i$), the reflected strain ($\in_r$), and the transmitted strain ($\in_i$). In order for these readings to be accurate, the correct two waves need to be picked up by the strain gages. These readings are depicted in Figure 4.

Based on the requirements set by the strain gage readings, the Incident Bar length comes out to be 274 mm and the Transmitter Bar length comes out to be 234 mm.

2C. Striker Bar Velocity

The striker bar velocity is crucial to reaching the desired strain rate for each test. By manipulating the striker bar velocity, the strain rate will increase or decrease in the same respect. In order to find the striker bar velocity, the desired stress (σ_{sp}) , strain rate, and strain in the specimen is needed. Along with this, the diameter of the specimen (D_{sp}) and bar (D_{bar}) will be needed in addition to the length of the specimen (L_{sp}). As a rule of thumb, the dimeter of the specimen needs to be less than half the diameter of the bar, while the length of the specimen needs to be between the diameter of the specimen and half the diameter of the specimen. This rule of thumb is important in order to have some amount of stress travel through the specimen into the transmitter bar, and some amount reflected back into the incident bar. If the diameter of the specimen was as large as the diameter of the bar, the test would be useless since no stress would be reflected back through the incident bar. If the diameter of the specimen was too small, the opposite would occur. All of the stress would be reflected back through the incident bar and none would travel into the transmitter bar.

This rule of thumb makes these parameters dependent upon the diameter of the bar and leaves two unknown variables, bar diameter and striker bar velocity. Equation 5 through Equation 12 show the calculations used to find the striker bar velocity. [9]

$$Reflected\ Strin: \epsilon_r = \frac{\dot{\epsilon_s} * L_{sp}}{2 * C_b} \quad [5]$$

$$Strain\ Rate\ in\ Specimen: \dot{\epsilon_{sp}} = \frac{2C_b \epsilon_r}{L_{sp}} \quad [6]$$

$$Transmitted\ Stress:\ \sigma_{trans} = \frac{\sigma_{sp} A_{sp}}{A_{bar}} \quad [7]$$

$$Transmited\ Strain:\ \ \epsilon_t = \frac{\sigma_{trans}}{E} \quad [8]$$

$$\epsilon_t = \epsilon_i + \epsilon_r \quad [9]$$

$$Incident\ Stress = \sigma_i = E\ \epsilon_i \quad [10]$$

$$Particle\ Velocity = v = \frac{\sigma_i}{\rho C_b} \quad [11]$$

$$Striker\ Bar\ Velocity = v_{striker} = 2v \quad [12]$$

These equations were plugged into a matlab code (Appendix A) and ran with a number of bar diameters in order to create Table 1.

Bar Diameter [mm]	2	1.5	1	0.5
Striker Bar Velocity [m/s]	23.3638	20.8634	18.363	15.8627

Table 1: Striker Bar Diameter and Velocity

After consideration, the bar diameter of 1mm was chosen. The reasoning behind this decision was that the velocity is obtainable, while the bar diameter is large enough to attach strain gages.

Chapter 3: Miniature Split Hopkinson Bar Design

3A. Load Creation

The most difficult part of the design process was determining how to shoot the striker bar at a velocity of roughly 18 m/s. The initial ideas of a spring mechanism, rack and pinion, or a counterweight mechanism were all dismissed for various reasons, such as too large of a force required to load the mechanism or the velocity not reaching 18 m/s in a short enough distance.

The idea for the use of a pressure gun was discussed. This would create a large enough velocity for the miniature split Hopkinson bar to be successful, but it would also be limited to a strain rate in the low 10^4 s^{-1} while still being at a safe pressure. Along with this limitation, the pressure gun is sometimes difficult to set up and tests involving it take more time.

In order to counteract these set-backs, a design using a cantilever beam was created. Figure 5 shows the cantilever beam system.

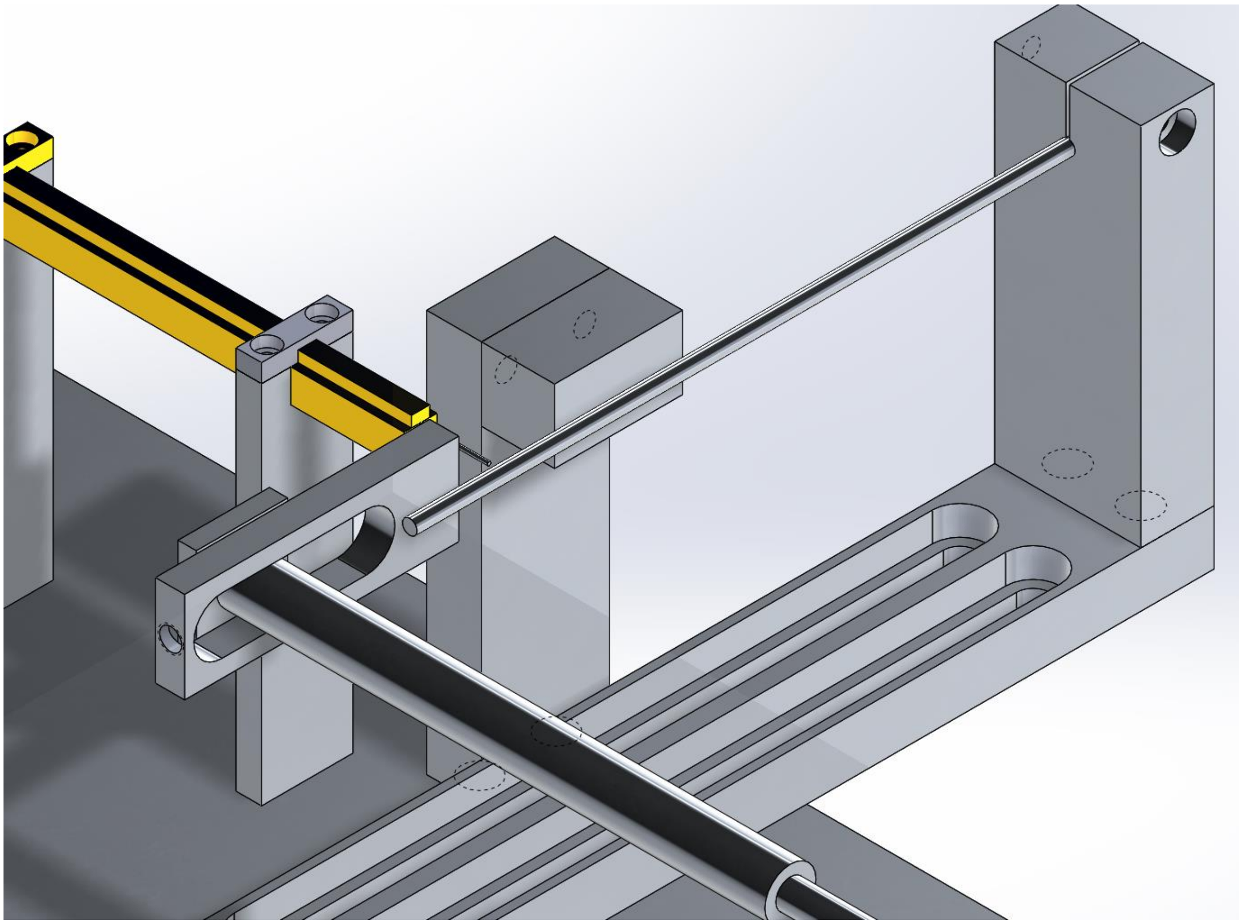

Figure 5: Cantilever Beam Set-up

As can be seen, there is a mechanism that pulls back a rod to a set distance. This mechanism is then disengaged from the rod in order for the rod to shoot forward uninhibited, pushing the striker bar, and creating the desired velocity.

A test independent of the MSHB was ran using a 1060 aluminum bar as the cantilever beam in order to determine the velocity which the end of the beam could reach. High speed cameras were used and the aluminum bar was tested at different amounts of deflection and lengths. The greatest velocity created during this test was roughly 18 m/s.

In order to account for friction forces in the MSHB, it was decided upon to use a higher grade of aluminum in the final design. Aluminum 7075 was decided upon, with the option to change material in the future to create a higher or lower strain rate depending on what is needed.

3B. General Design

The final design of the MSHB can be found in Figure 6.

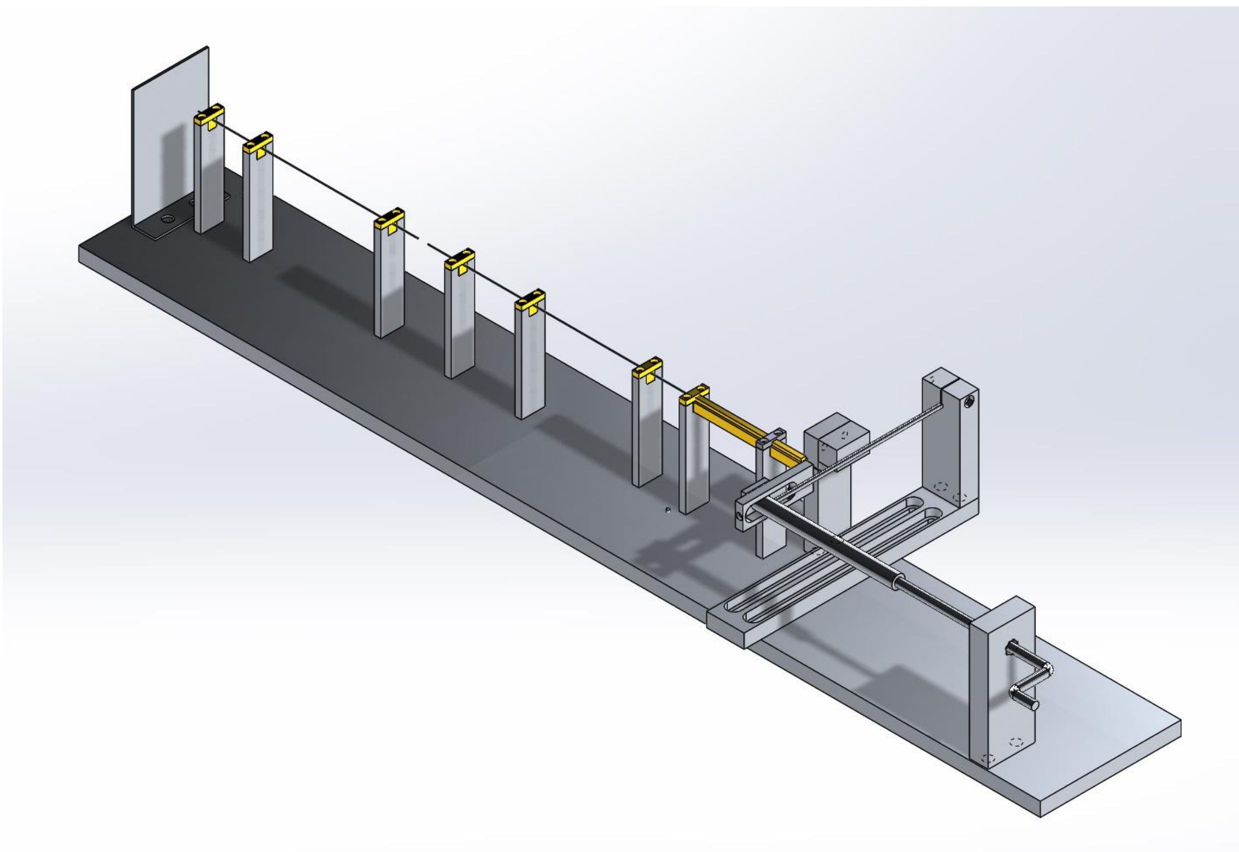

Figure 6: Final Design

Each bar is be supported by a brass “V” shaped support which can be seen in Figure 7.

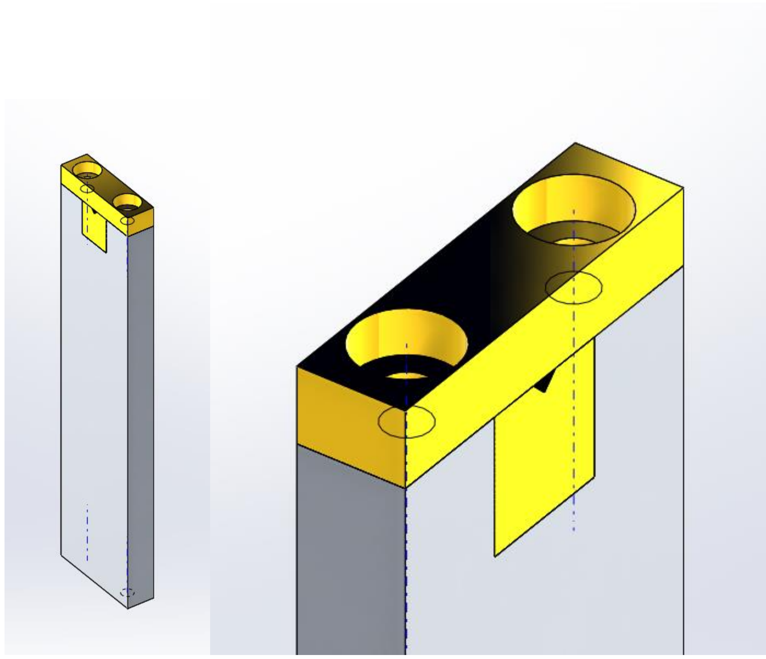

Figure 7: Bar Supports

Brass was used in order to reduce the friction on the bars, and keep a high enough velocity required to create the desired strain rate. The “V” shape support gives this design the ability to use larger diameter bars if desired in the future.

The support directly in front of the Cantilever beam is in the shape of a trough in order to give the striker bar the ability to extrude from the support while staying aligned with the other bars. This is crucial for the solid contact between the striker bar and incident bar.

The strain gages are located in the middle of the incident and transmitter bars per the initial design requirements.

Chapter 4: Results and Discussion

After manufacturing and assembly, the Miniature Split Hopkinson Bar can be seen in Figure 8 and Figure 9.

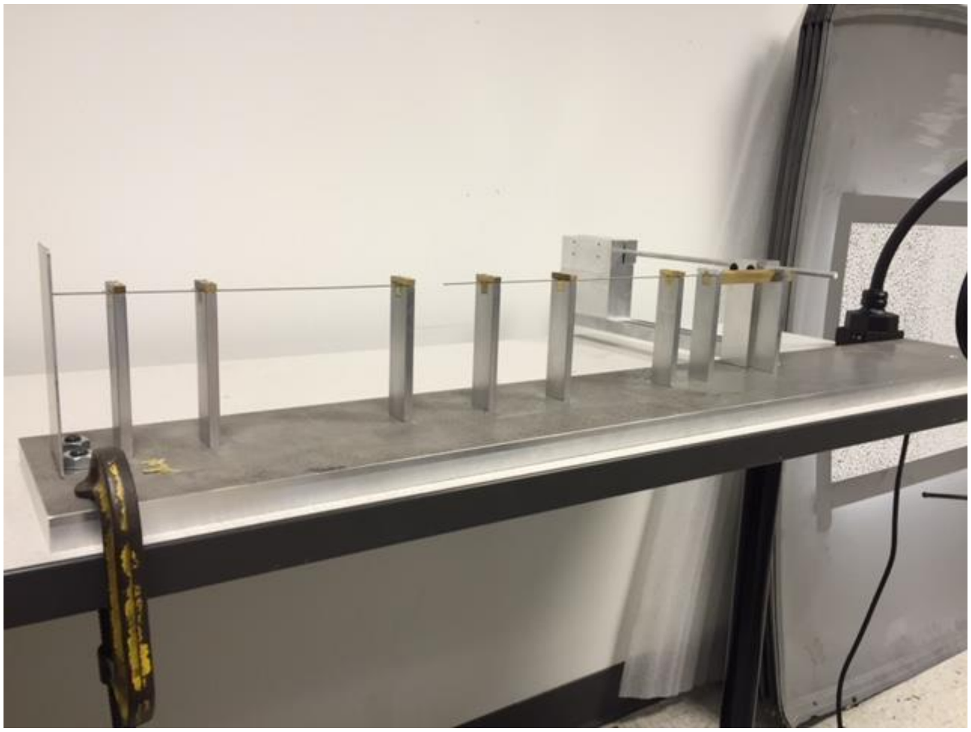

Figure 8: Miniature Compressive Split Hopkinson Bar

Figure 9: Load Supply-Cantilever Beam

For testing purposes, the first step was to measure the maximum obtainable velocity of the striker bar. The set-up for obtaining this can be seen in Figure 10.

Figure 10: Test Set-up

A high speed camera was placed in front of the striker bar and incident bar collision point. Data was then collected with the cantilever beam set at different lengths and pulled back to different distances. The maximum velocity obtained was 19 m/s. Figure 11 shows the test in which this velocity was obtained.

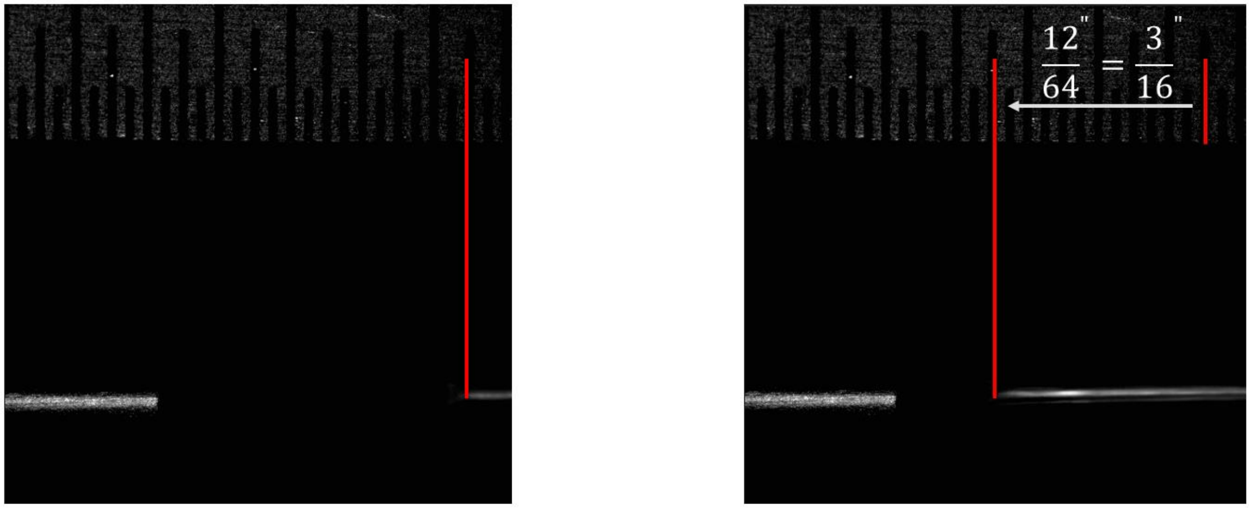

Figure 11: 19 m/s Test Results

The high speed camera was set to take 4000 frames per second and the scale above the striker bar has a distance of 1/64" for each mark. These two pictures are one frame apart and therefore with the calculation in Equation 13, the velocity of the striker bar is 19 m/s.

$$\frac{\frac{12}{64}\,in}{1\,frame} * \frac{4000\,frames}{second} * \frac{0.0254\,m}{1\,in} = 19.05\,\frac{m}{s} \qquad [13]$$

Using the velocity of 19 m/s, Table 2 was created in order to show the respective strain rates when testing different materials with different ultimate strengths and separate specimen diameters.

Material	Striker Bar Velocity [m/s]	Specimen Diameter [mm]	Ultimate Stress [MPa]	Strain Rate [s^{-1}]
Aluminum 6061	19	0.5	310	24,000
Brass	19	0.5	345	22,600
304 Stainless Steel	19	0.5	505	15,500
1090 Carbon Steel	19	0.4	841	17,500
Annealed Titanium	19	0.4	950	13,600
Annealed Titanium	19	0.3	950	37,900

Table 2: Final Results

Chapter 5: Conclusions and Recommendations

The design of this Miniature Split Hopkinson Bar was successful. The design has the capability to test certain materials at an extremely high strain rate. This particular design is limited to a minimum amount of strain rate based on the amount of strain desired. In most metal samples, the strain should be greater than 0.25 in order to encompass the material's properties. This would limit the MSHB to a minimum strain rate of 5000 s^{-1}.

The next step is to create consistent tests. Moving forward, some things can be adapted in order for the MSHB to test at a consistent strain rate. The main component that was slowing down the striker bar and creating inconsistencies was the lack of straightness in the bars. An extremely straight 1mm bar is very difficult to find and maintain. However, it would definitely be possible to find bars straighter than the ones used during these tests. These straighter bars would greatly reduce friction on the striker bar and in-turn increase consistency in the test.

Another option would be to increase the bar diameter. The design of the MSHB has the capability to use a 2mm bar. This increase in diameter would increase the required velocity by roughly 5 m/s. However, it would be easier to find a very straight 2mm bar of titanium and this increase in straightness would decrease the velocity loss due to friction and in turn create consistent tests.

Moving forward, the MSHB will have strain gages attached to the incident and transmitter bars. Once these are attached, specimens will be made and the MSHB will be used for testing purposes.

References

[1] Hammer, Jeremiah: "Plastic Deformation and Ductile Fracture of Ti-6Al-4V under Various Loading Conditions" 2012

[2] Dynamic Mechanics of Materials Laboratory: "High Strain Rate Compression Tests" "Figure 1: Sketch of a Compression Split Hopkinson Bar Apparatus" http://www.mecheng.osu.edu/lab/dmm/node/34

[3] Altman, Allison; Davis, Irene; "Comparison of Tibial Strains and Strain Rates in Barefoot and Shod Running"

[4] Photo; http://www.dreamstime.com/photos-images/car-accident-cartoon.html

[5] Harms, Ulrich; Koeberl, Christian; "Continental Scientific Drilling: A decade of Progress, and Challenges"

[6] Doss, HM; "Bullet Proof: Absorbing Micro-Bullets" http://www.physicscentral.com/explore/action/bullet-proof.cfm

[7] Kimberly, Jamie; Paul, Jastin; "A Miniature Tensile Kolsky Bar for Thin film Testing"

[8] Siviour, Clive; Jordan, Jennifer; "A Miniature Split Hopkinson Pressure Bar for Very High Strain Rate Testing" Air Force Research Laboratory

[9] Gray III, George T; Article: "Classic Split-Hopkinson Pressure Bar Testing"; "Mechanical Testing and Evaluation, Volume 8" pgs 462-474

Appendix A

```
%Striker Velocity
clc
clear
format short
format compact

% 2mm
% Bar Ti-6Al-4V
Cb=5.068*10^3;        %[m/s]
E=113.8*10^9;      %[GPa]
p=4430;      %[kg/m^3]
D=2*10^-3;      %[m]
A_bar=pi*(.5*D)^(2);

%Specimen
Ds=0.5*D;     %[m]
Ls=Ds;
As=pi*(0.5*Ds)^(2);

e_dot=10000;      %[1/s]
stress=600*10^6; %[Pa]

e_R=(e_dot*Ls)/(2*Cb);
stress_T=(stress*As)/A_bar;
e_T=stress_T/E;

e_I=e_T+e_R;
stress_I=E*e_I;

v_specimen=stress_I/(p*Cb);
v_striker_2mm=2*v_specimen

% 1.5mm
D=1.5*10^-3;      %[m]
A_bar=pi*(.5*D)^(2);

%Specimen
Ds=0.5*D;     %[m]
Ls=Ds;
As=pi*(0.5*Ds)^(2);


e_R=(e_dot*Ls)/(2*Cb);
stress_T=(stress*As)/A_bar;
e_T=stress_T/E;

e_I=e_T+e_R;
stress_I=E*e_I;

v_specimen=stress_I/(p*Cb);
v_striker_1_half_mm=2*v_specimen
```

```
% 1mm
D=1*10^-3;      %[m]
A_bar=pi*(.5*D)^(2);

%Specimen
Ds=0.5*D;     %[m]
Ls=Ds;
As=pi*(0.5*Ds)^(2);


e_R=(e_dot*Ls)/(2*Cb);
stress_T=(stress*As)/A_bar;
e_T=stress_T/E;

e_I=e_T+e_R;
stress_I=E*e_I;

v_specimen=stress_I/(p*Cb);
v_striker_1mm=2*v_specimen

% 0.5mm
D=0.5*10^-3;      %[m]
A_bar=pi*(.5*D)^(2);

%Specimen
Ds=0.5*D;     %[m]
Ls=Ds;
As=pi*(0.5*Ds)^(2);


e_R=(e_dot*Ls)/(2*Cb);
stress_T=(stress*As)/A_bar;
e_T=stress_T/E;

e_I=e_T+e_R;
stress_I=E*e_I;

v_specimen=stress_I/(p*Cb);
v_striker_half_mm=2*v_specimen
```